**REVIEW** | **OPEN ACCESS**

# Medical Science

**To Cite:**
Stremel A, Bachoń E, Siemianowski J, Doligalska M, Kotnis W, Bałoniak Z, Leszyńska A, Jonkisz A, Bałoniak J, Skurzyńska G. Risk factors of Anterior Crucial Ligament injuries in alpine skiing. A review of the literature. *Medical Science* 2024; 28: e154ms3495
doi: https://doi.org/10.54905/disssi.v28i154.e154ms3495

**Authors' Affiliation:**
[1]Centre of Postgraduate Medical Education, Orłowski Hospital, Czerniakowska 231, 00-416, Warsaw, Poland
[2]Clinical Hospital in Poznan, Przybyszewskiego 49, 60-355 Poznań, Poland
[3]Central Teaching Hospital of the Medical University of Lodz, Pomorska 251, 92-213 Łódź, Poland
[4]Medical Hospital in Garwolin, Lubelska 50, 08-400 Garwolin, Poland
[5]Medical University of Lodz, Kościuszki 4, 90-419 Łódź, Poland
[6]Warsaw Southern Hospital, Rotmistrza Witolda Pileckiego 99, 02-781 Warszawa, Poland
[7]Poznan University of Medical Sciences, Collegium Maius, Fredry 10, 61-701 Poznań, Poland
[8]District Health Center in Otwock, Batorego 44, 05-400 Otwock, Poland

*Corresponding Author
Centre of Postgraduate Medical Education, Orłowski Hospital, Czerniakowska 231, 00-416, Warsaw,
Poland
Email: ola.stremel@gmail.com

**Peer-Review History**
Received: 07 September 2024
Reviewed & Revised: 11/September/2024 to 14/December/2024
Accepted: 18 December 2024
Published: 27 December 2024

**Peer-review Method**
External peer-review was done through double-blind method.

Medical Science
pISSN 2321–7359; eISSN 2321–7367



DISCOVERY SCIENTIFIC SOCIETY

# Risk factors of Anterior Crucial Ligament injuries in alpine skiing. A review of the literature

**Aleksandra Stremel[1*], Emilia Bachoń[2], Jan Siemianowski[3], Michalina Doligalska[4], Weronika Kotnis[5], Zuzanna Bałoniak[6], Agnieszka Leszyńska[7], Aleksandra Jonkisz[2], Julia Bałoniak[2], Gabriela Skurzyńska[8]**

## ABSTRACT

Anterior cruciate ligament (ACL) injuries are the most frequently occurring knee injuries in alpine skiing and represent a significant challenge for both professional athletes and recreational participants. Women with their combination of biomechanical and hormonal risks, as well as novice skiers with their skill-related influences, are particularly vulnerable to ACL injury. These injuries account for 15–21% of all knee traumas in the sport, often stemming from noncontact mechanisms like twisting falls or improper weight distribution during dynamic maneuvers. The injury risk can be amplified by the interaction between intrinsic factors, such as sex, age, anatomical characteristics, neuromuscular imbalances, and extrinsic elements, including equipment setup and environmental conditions. Females exhibit a threefold higher risk than males, influenced by hormonal and biomechanical differences, while side-to-side knee laxity and neuromuscular asymmetries heighten susceptibility in competitive athletes. Equipment, mainly worn ski boot soles or misadjusted bindings, contributes to accidents by compromising ski-boot-binding functionality. Preventative strategies targeting neuromuscular training, proper equipment maintenance, and education about environmental adaptations show promise in mitigating the risk of injury due to environmental factors like icy or grippy snow and cold temperatures. However, reinjury remains a concern, especially for adolescents returning to sport within two years post-ACL reconstruction. Through reviewing 28 studies, this paper creates an overview of the multifactorial cause of ACL injuries in skiing to indicate the need for individually tailored prevention strategies and to stimulate further research regarding risk-reducing interventions in skiing.

**Keywords:** Knee, Anterior cruciate ligament (ACL), Alpine skiing, Risk factors, Injury

## 1. INTRODUCTION

Anterior cruciate ligament (ACL) injuries dominate as the most frequent knee injuries in alpine skiing, presenting significant challenges to both competitive athletes and recreational participants (Ruedl et al., 2023; Posch et al., 2019). These injuries carry profound physical and psychological consequences, often requiring extensive rehabilitation and long-term management (Posch et al., 2021; Westin et al., 2018). Despite advancements in injury prevention, ACL injuries remain prevalent, particularly in skiing - a sport that combines high speeds, rapid direction changes, and varied environmental conditions (Posch et al., 2023; Ruedl et al., 2023).

Multiple intrinsic and extrinsic factors influence ACL injury risk. Among intrinsic factors, biological sex plays a critical role; females show a threefold higher likelihood of sustaining ACL injuries compared to males (Posch et al., 2019). Hormonal fluctuations, anatomical differences, and neuromuscular control disparities, such as quadriceps dominance and side-to-side knee laxity, amplify this vulnerability (Promsri et al., 2019; Westin et al., 2018). Adolescent skiers also exhibit heightened susceptibility due to ongoing musculoskeletal development, while competitive athletes face compounded risks from intense physical demands and frequent exposure (Westin et al., 2018).

Extrinsic factors further complicate the landscape. Equipment-related issues, such as worn ski boot soles, improperly adjusted bindings, and mismatched ski length, contribute significantly to injury risk by disrupting the ski-boot-binding unit's functionality (Posch et al., 2019; Ruedl et al., 2023). Environmental elements, including icy slopes, variable snow conditions, and extreme temperatures, exacerbate these challenges by altering skiing dynamics and increasing fall likelihood (Posch et al., 2023; Posch et al., 2019).

Noncontact mechanisms dominate ACL injury causation in skiing, with twisting falls and improper weight distribution during high-speed maneuvers frequently reported (Ruedl et al., 2023). A holistic strategy composed of neuromuscular training to improve balance and proprioception, strict equipment upkeep, and education on how to adapt to different conditions is essential in preventing these hazards (Posch et al., 2019). However, reinjury rates, especially among young athletes post-ACL reconstruction, highlight gaps in current preventive strategies (Westin et al., 2018; Posch et al., 2019).

## 2. METHODOLOGY

This paper comprehensively reviews some of the already published literature on ACL injuries. Using a database of 28 articles, we created an article highlighting the importance of intrinsic and extrinsic risk factors and injury biomechanics in determining injury severity. Literature was sourced from the PubMed database, covering publications from 2005 to 2024. The review included meta-analyses, observational studies, and systematic reviews. Relevant articles were identified using search terms such as "ACL injury in alpine skiing", "knee injuries", "alpine skiing contusions", "risk factors", and "physical activity". Studies were selected if they focused on influencing the increased chance of ACL damage.

## 3. RESULTS AND DISCUSSION

The anterior cruciate ligament (ACL) is the main structure maintaining the stability of the knee joint. ACL injuries are among the most severe and common injuries in sports and often result in osteoarthritis, decreased physical performance, and other long-term consequences. An understanding of the inherent risk factors can provide key findings for the development of effective prevention and recovery strategies. These factors include anatomical, genetic, hormonal, neuromuscular, cognitive, and historical injury-related considerations.

**Anatomical Factors**

Few anatomical differences are well-documented contributors to ACL injury risk. Variations such as a steeper posterior tibial slope and narrower intercondylar notch increase the susceptibility to ACL tears. These anatomical configurations amplify anterior tibial translation during activities that involve cutting or pivoting movements, placing additional strain on the ACL (Westin et al., 2018; Hagino et al., 2024; Gupta et al., 2020; Westin et al., 2022; Gupta et al., 2022). Sex-based differences also play a pivotal role. Female athletes are at a higher risk, often due to smaller ACL cross-sectional areas, higher quadriceps-to-hamstring strength ratios, and greater knee valgus angles during physical activity (Smith et al., 2012; Schmitt et al., 2016).

Studies show that these factors, paired with broader pelvises and increased joint laxity, create biomechanical conditions that heighten ACL stress during dynamic movements (Smith et al., 2012). There are discernible hereditary influences on anatomical features. Families with multiple members experiencing ACL injuries often exhibit shared characteristics, such as narrower notch widths or steeper tibial slopes (Hagino et al., 2024). These findings show how genetic and anatomical predisposition interplay in ACL injuries.

**Genetic Predisposition**

Genetic factors influencing ligament composition and repair mechanisms significantly affect ACL injury risks. Variants in the COL1A1 and COL5A1 genes, which encode collagen proteins vital for ligament integrity, have been associated with increased ACL tear susceptibility (Smith et al., 2012; Hagino et al., 2024). Familial clustering of ACL injuries further emphasizes the genetic component. Individuals with a first-degree relative who has suffered an ACL tear have a higher likelihood of experiencing a similar injury (Hagino et al., 2024). These genetic insights allow the identification of at-risk populations and tailoring prevention strategies.

**Hormonal Influences**

Hormones influence ligament properties, particularly in females, whose ACL injury rates are 2–8 times higher than their male counterparts in similar sports. Estrogen and progesterone fluctuation levels during the menstrual cycle affect ligament strength, stiffness, and joint laxity (Smith et al., 2012; Hagino et al., 2024). Increased estrogen levels during the ovulatory phase are associated with decreased ACL stiffness, leading to heightened injury risks during high-impact activities (Smith et al., 2012). While these hormonal effects are well-documented, their interactions with neuromuscular and biomechanical factors remain an area for further research.

**Neuromuscular Control**

Deficits in neuromuscular control are among the most modifiable intrinsic risk factors. Poor proprioception, delayed muscle activation, and imbalances between the hamstrings and the quadriceps can predispose individuals to ACL injuries (Westin et al., 2018; Schmitt et al., 2016; Promsri et al., 2019; Westin et al., 2022). In particular, "quadriceps dominance"—a condition where the quadriceps muscles overpower the hamstrings—places excessive strain on the ACL during deceleration and directional changes (Gupta et al., 2020; Promsri et al., 2019; Gupta et al., 2022).

Additionally, neuromuscular asymmetries, such as weaker control in the nondominant leg, are prevalent in athletes and skiers, further increasing injury risks (Promsri et al., 2019; Westin et al., 2018; Westin et al., 2020). Preventive neuromuscular training programs have demonstrated efficacy in reducing these deficits. Very beneficial in ACL injury prevention are exercises focusing on balance, coordination, and symmetric leg strength (Westin et al., 2018; Westin et al., 2020).

**Cognitive and Perceptual Factors**

Cognitive elements, including reaction time, decision-making, and spatial awareness, are emerging as significant contributors to ACL injury risk. High-stakes sports like skiing require rapid adaptation to unpredictable environments. Cognitive overload during competition can impair motor planning, leading to delayed reactions and improper biomechanical alignments (Motififard et al., 2024; Westin et al., 2018; Smith et al., 2024; Westin et al., 2020). Athletes recovering from ACL injuries may exhibit deficits in perceptual-motor integration due to neuroplastic changes in response to injury. These alterations may persist even after biomechanical recovery, potentially explaining high reinjury rates (Motififard et al., 2024; Smith et al., 2024).

**Knowledge and Awareness**

Lack of consciousness of proper movement techniques and injury prevention strategies can increase the likelihood of ACL injuries. Crucial for prevention are educational programs emphasizing safe landing mechanics, proper cutting techniques, and risk factor identification. Studies show a significant injury rate reduction following the implementation of structured awareness and neuromuscular training programs (Westin et al., 2018; Westin et al., 2020; Westin et al., 2022).

**History of Previous Injuries**

A history of ACL injury is one of the strongest predictors of future injuries. The risk is compounded by altered biomechanics, incomplete rehabilitation, and compensatory strategies that shift stress onto the contralateral limb (Westin et al., 2018; Smith et al., 2012; Westin et al., 2022). Previous ACL injuries significantly increase the risk of reinjury due to persistent neuromuscular deficits and biomechanical asymmetries that may not fully resolve after rehabilitation (Jordan et al., 2017). Young athletes returning to high-intensity sports too soon after reconstruction are particularly vulnerable. Research indicates that within two years of returning to the sport, nearly 20–30% of athletes suffer either a reinjury to the same knee or a new injury to the opposite knee (Westin et al., 2018; Smith et al., 2012; Motififard et al., 2024).

**Integration of Risk Factors**

Intrinsic risk factors for ACL injuries encompass anatomical, genetic, hormonal, neuromuscular, cognitive, and historical components (Table 1). While each independently contributes to ACL injury risks, their compilation often amplifies susceptibility. Awareness of these interactions can help develop unique prevention strategies. A multidisciplinary approach required for addressing these factors is composed of education, neuromuscular training, biomechanical assessments, and genetic screening. Such integrated strategies hold promise for reducing injury rates and improving long-term outcomes for at-risk individuals.

**Table 1** Intrinsic risk factors

| **Intrinsic Risk Factor** | **Description** | **Consequences** | **Source Paragraphs** |
|---|---|---|---|
| Anatomical Factors | Steeper posterior tibial slope, narrower intercondylar notch, smaller ACL cross-sectional area, and increased knee laxity. | Increased susceptibility to ACL stress and tears, particularly during high-impact activities. | (Westin et al., 2022; Hagino et al., 2024; Gupta et al., 2022) |
| Genetic Predisposition | Variants in collagen-related genes (e.g., COL1A1, COL5A1) and familial patterns of ACL injuries. | Higher likelihood of ACL injuries within families and increased risk even with low external stress. | (Smith et al., 2012; Hagino et al., 2024) |
| Hormonal Influences | Hormonal fluctuations, particularly increased estrogen during the ovulatory phase, reduce ligament stiffness. | Greater ligament laxity and reduced tensile strength, leading to higher risk during dynamic activities. | (Smith et al., 2012; Hagino et al., 2024) |
| Neuromuscular Control | Poor proprioception, delayed muscle activation, quadriceps dominance, and leg strength asymmetry. | Reduced dynamic stability, leading to improper landing mechanics and higher strain on the ACL. | (Westin et al., 2022; Schmitt et al., 2016; Promsri et al., 2019) |
| Cognitive and Perceptual Factors | Impaired reaction time, decision-making deficits, and altered perceptual-motor integration following injury. | Delayed reactions and compensatory movement patterns, increasing the risk of falls and ACL stress. | (Smith et al., 2024; Westin et al., 2020) |
| Knowledge and Awareness | Lack of understanding of proper techniques and injury prevention strategies. | Increased exposure to risky movements and decreased ability to avoid high-stress knee positions. | (Westin et al., 2020; Westin et al., 2022) |
| Previous Injuries | History of ACL injuries significantly increases re- | Elevated likelihood of subsequent ACL injuries to | (Westin et al., 2022; Smith et al., 2012; Smith et al., 2024; |

| | | | |
|---|---|---|---|
| | injury risk due to residual neuromuscular and biomechanical deficits. | the same or contralateral knee, impacting long-term outcomes. | Jordan et al., 2017) |

**Extrinsic Risk Factors for ACL Injury in Alpine Skiing: Equipment, Snow, Course, and Weather**

Extrinsic risk factors, encompassing equipment, snow conditions, course design, and weather, significantly influence the likelihood of Anterior Crucial Ligament (ACL) injuries. These factors operate independently or interactively, highlighting the complexity of injury causation in this sport (Ruedl et al., 2023; Davey et al., 2019; Westin et al., 2018; Posch et al., 2023; Ruedl et al., 2022).

**Equipment**

Ski equipment plays a pivotal role in ACL injury risk. Research suggests that 80% of lower extremity injuries in skiing are equipment-related, largely due to skis acting as levers that amplify forces on the knee (Ruedl et al., 2023; Davey et al., 2019; Ruedl et al., 2022). Rental skis, which are often shorter with reduced side-cut radii and narrower dimensions, have been associated with increased injury risks, potentially due to their lack of customization to individual skier needs (Ruedl et al., 2023; Posch et al., 2023; Ruedl et al., 2022).

Furthermore, worn or improperly maintained ski boots, particularly those with excessive sole abrasion, can impair the release mechanism of ski bindings, leading to a higher likelihood of injury during falls (Posch et al., 2019; Posch et al., 2023). The standing height ratio, which reflects the differential elevation between the front and rear components of the binding system, is another crucial factor. Elevated risk of ACL injuries is linked to a higher standing height ratio because it compromises the skier’s control and increases susceptibility to rotational forces during falls (Ruedl et al., 2023; Davey et al., 2019; Posch et al., 2019; Ruedl et al., 2022).

**Snow Conditions**

The condition of the snow significantly influences skiing dynamics and injury risk. Icy snow increases the likelihood of ACL injuries due to reduced traction, which limits control during turns and sudden stops (Posch et al., 2023; Westin et al., 2018). On the other hand, fresh or grippy snow also elevates injury risks by increasing the likelihood of abrupt halts and rotational forces on the knee (Posch et al., 2023; Spörri et al., 2012; Posch et al., 2019). Mixed conditions, where icy patches transition into softer snow, can lead to a higher risk of injury because of instability caused by unexpected changes in ski-surface interaction (Davey et al., 2019; Posch et al., 2023).

**Course Design**

The layout and features of a ski course can significantly affect injury risks. Sharp turns, steep slopes, and high-speed sections demand greater technical skills and increase the likelihood of errors (Tarka et al., 2019; Spörri et al., 2012). Counterintuitively, flat and easy slopes have been linked to higher ACL injury rates due to a tendency among skiers to underestimate risks and engage in less controlled skiing (Posch et al., 2023). Poor visibility and inadequate course marking further compromise safety, as they reduce the skier's ability to navigate effectively and anticipate hazards (Spörri et al., 2012; Posch et al., 2019; Posch et al., 2023).

**Weather**

Weather conditions influence the environment on ski slopes and the likelihood of ACL injuries. Cold temperatures, particularly those below -8°C, contribute to harder snow, increasing the impact forces during falls (Posch et al., 2023; Posch et al., 2022; Posch et al., 2021). Snowfall and fog impair visibility, making it more challenging for skiers to anticipate obstacles or changes in slope conditions (Posch et al., 2019; Posch et al., 2023; Westin et al., 2018). Wind and fluctuating temperatures can create uneven snow surfaces, increasing injury risks (Westin et al., 2018; Posch et al., 2023).

**Integrated Impact of Extrinsic Factors**

The overall risk can be amplified by interaction of these extrinsic factors. To be effective, prevention strategies should take account of these multiple risks, considering both environmental conditions and the optimization of ski equipment (Posch et al., 2019; Posch et al., 2023). Extrinsic factors significantly contribute to the prevalence of ACL injuries in recreational alpine skiing. Properly maintained equipment, better snow preparation, optimized course design, and consideration of weather conditions can mitigate these risks.

Stakeholders, including ski resort operators, equipment manufacturers, and safety advocates, must prioritize these factors to enhance skier safety and minimize injury rates (Davey et al., 2019; Westin et al., 2018; Posch et al., 2019; Posch et al., 2023).

**The Influence of Biomechanics and Injury Mechanisms on ACL Injury Severity**

Anterior cruciate ligament (ACL) injuries are among the most debilitating sports injuries, with their severity significantly influenced by the biomechanics of the knee joint and the mechanism of injury. These injuries predominantly result from activities that involve sudden changes in direction, landing from a jump, or high external forces (Yu & Garrett, 2007). The variability in biomechanical and external factors contributing to ACL injuries provides a foundation for understanding their severity and guiding prevention strategies (Spörri et al., 2012; Hewett et al., 2005; Spörri et al., 2022).

**Mechanisms of ACL Injuries**

ACL injuries are commonly categorized into contact and noncontact mechanisms, with each mode displaying unique biomechanical implications (Larwa et al., 2021). Noncontact injuries, which dominate cases in sports like skiing, basketball, and soccer, often arise from abrupt deceleration, cutting, or awkward landings (Gupta et al., 2020; Heinrich et al., 2023; Hewett et al., 2005). For example, studies in skiing highlight mechanisms like the "slip-catch" or "dynamic snowplough", where sudden changes in ski-surface interaction lead to excessive knee valgus and internal rotation (Spörri et al., 2012; Heinrich et al., 2023).

In contrast, contact injuries involve external forces acting directly on the knee, such as collisions during gameplay. These mechanisms result in different loading patterns, frequently leading to additional structural damage in the knee (Gupta et al., 2020; Spörri et al., 2022; Spörri et al., 2012). Importantly, noncontact injuries are associated with a higher incidence of concomitant meniscal and chondral damage, complicating recovery and increasing injury severity (Gupta et al., 2020).

**Biomechanical Factors Influencing Injury Severity**

The biomechanical environment of the knee during high-risk movements significantly impacts the likelihood and severity of ACL injuries. Dynamic valgus loading—a combination of knee abduction and external forces—has been identified as a critical predictor of ACL injuries, particularly in female athletes (Hewett et al., 2005). For example, neuromuscular imbalances such as ligament dominance or quadriceps dominance exacerbate the risk, as they result in insufficient absorption of ground reaction forces by the muscular system, increasing stress on the ligament (Hewett et al., 2005; Boden et al., 2010). Further, the degree of knee flexion during injury-inducing movements also determines the extent of ligament strain. Studies have shown that greater knee flexion angles tend to reduce anterior tibial translation and distribute forces more evenly across the knee joint (Heinrich et al., 2023; Hewett et al., 2005).

**Associated Injuries and Long-Term Implications**

Concomitant injuries, such as meniscal tears and chondral damage, frequently accompany ACL ruptures, especially in noncontact mechanisms (Gupta et al., 2020; Spörri et al., 2012; Spörri et al., 2022). In alpine skiing, the aggressive interaction between the ski and snow can amplify ground reaction forces, leading to multi-structure knee injuries (Posch et al., 2021; Heinrich et al., 2023). These associated injuries not only increase immediate injury severity but also prolong recovery times and heighten the risk of osteoarthritis (Heinrich et al., 2023; Motififard et al., 2024; Smith et al., 2024).

**The Role of Equipment and Environmental Factors**

External factors such as ski geometry, binding settings, and snow conditions predominantly influence ACL injury severity. Improper ski binding settings have been implicated in the failure to release during falls, leading to excessive rotational forces on the knee (Spörri et al., 2012; Motififard et al., 2024; Spörri et al., 2022; Smith et al., 2024). Other factors also increase the biomechanical load on the ACL. Those can include uneven snow surfaces or low visibility which lead to unpredictable perturbations (Spörri et al., 2012; Motififard et al., 2024; Spörri et al., 2022; Smith et al., 2024).

A better understanding of the causes of injury of ACL ruptures and the underlying biomechanics can help develop prevention strategies. (Shimokochi and Shultz, 2008). The initial severity and long-term outcomes are determined by the mode of injury, biomechanical loads, and external influences. Preventative measures, including neuromuscular training, equipment optimization, and

environmental adjustments, are essential to mitigate these injuries and improve rehabilitation outcomes (Spörri et al., 2012; Motififard et al., 2024; Spörri et al., 2022; Smith et al., 2024).

## 4. CONCLUSION

ACL injuries in alpine skiing stem from a combination of personal, equipment-related, and environmental factors, each adding layers of complexity to prevention and management efforts. Intrinsic risk factors, such as anatomical variations, hormonal changes, neuromuscular deficiencies, and genetic predispositions, are particularly pronounced in female skiers and adolescents who encounter unique biomechanical and developmental vulnerabilities. Extrinsic factors, including poorly maintained equipment, specific snow conditions, challenging course designs, and extreme weather conditions, further heighten the risk of injury and can result in additional knee damage, which can prolong recovery and lead to long-term complications such as joint instability and osteoarthritis.

Addressing ACL injuries requires a comprehensive, multifactorial approach, and prioritizing physical conditioning, neuromuscular training, and biomechanical improvements is an essential strategy. Proper maintenance and individualized equipment adjustment, alongside educating skiers on techniques suited to varying snow and weather conditions, can minimize the risk of ACL injury. Collaboration among coaches, healthcare providers, equipment designers, and ski resort operators is essential to establish and maintain safer practices on the slopes. Continued research and innovation are crucial to advancing these prevention strategies. Incorporating insights from biomechanical research, injury tracking, and rehabilitation studies can lead to more effective interventions. A holistic approach that integrates these efforts offers the most significant potential to reduce ACL injury rates, improve skier safety, and sustain long-term sports participation.

**Authors' Contribution**

Aleksandra Stremel: Conceptualization, writing- rough preparation, investigation
Emilia Bachoń: Formal analysis, supervision
Jan Siemianowski: Visualization, supervision
Michalina Doligalska: Conceptualization, project administration
Weronika Kotnis: Methodology, data curation
Zuzanna Bałoniak: Conceptualization, methodology
Agnieszka Leszyńska: Resources, writing- rough preparation
Aleksandra Jonkisz: Conceptualization, writing- rough preparation
Julia Bałoniak: Resources, data curation
Gabriela Skurzyńska: Writing - Review and editing, supervision
All authors have read and agreed to the published version of the manuscript.

**Acknowledgments**

No acknowledgments.

**Ethical approval**

Not applicable.

**Informed consent**

Not applicable.

**Funding**

This study has not received any external funding.

**Conflict of interest**

The authors declare that there is no conflict of interests.

**Data and materials availability**

All data sets collected during this study are available upon reasonable request from the corresponding author.

## REFERENCES


1. Boden BP, Sheehan FT, Torg JS, Hewett TE. Noncontact anterior cruciate ligament injuries: mechanisms and risk factors. J Am Acad Orthop Surg 2010; 18(9):520-7. doi: 10.5435/00124635-201009000-00003
2. Davey A, Endres NK, Johnson RJ, Shealy JE. Alpine Skiing Injuries. Sports Health 2019; 11(1):18-26. doi: 10.1177/1941738118813051
3. Gupta R, Jhatiwal S, Kapoor A, Kaur R, Soni A, Singhal A. Narrow Notch Width and Low Anterior Cruciate Ligament Volume Are Risk Factors for Anterior Cruciate Ligament Injury: A Magnetic Resonance Imaging-Based Study. HSS J 2022; 18(3):376-384. doi: 10.1177/15563316211041090
4. Gupta R, Kapoor A, Soni A, Khatri S, Masih GD. Anterior cruciate ligament tear due to non-contact mode of injury associated with higher incidence of meniscal and chondral damage. J Clin Orthop Trauma 2020; 11(Suppl 3):S342-S345. doi: 10.1016/j.jcot.2019.07.012
5. Hagino T, Ochiai S, Furuya N, Hagino T, Wako M, Taniguchi N, Haro H. Hereditary Anatomical Risk Factors for Anterior Cruciate Ligament Injuries. Cureus 2024; 16(2):e55129. doi: 10.7759/cureus.55129
6. Heinrich D, Van-den-Bogert AJ, Mössner M, Nachbauer W. Model-based estimation of muscle and ACL forces during turning maneuvers in alpine skiing. Sci Rep 2023; 13(1):9026. doi: 10.1038/s41598-023-35775-4
7. Hewett TE, Myer GD, Ford KR, Heidt RS Jr, Colosimo AJ, McLean SG, Van-den-Bogert AJ, Paterno MV, Succop P. Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: a prospective study. Am J Sports Med 2005; 33(4):492-501. doi: 10.1177/0363546504269591
8. Jordan MJ, Aagaard P, Herzog W. Anterior cruciate ligament injury/reinjury in alpine ski racing: a narrative review. Open Access J Sports Med 2017; 8:71-83. doi: 10.2147/OAJSM.S106699
9. Larwa J, Stoy C, Chafetz RS, Boniello M, Franklin C. Stiff Landings, Core Stability, and Dynamic Knee Valgus: A Systematic Review on Documented Anterior Cruciate Ligament Ruptures in Male and Female Athletes. Int J Environ Res Public Health 2021; 18(7):3826. doi: 10.3390/ijerph18073826
10. Motififard M, Akbari-Aghdam H, Ravanbod H, Jafarpishe MS, Shahsavan M, Daemi A, Mehrvar A, Rezvani A, Jamalirad H, Jajroudi M, Shahsavan M. Demographic and Injury Characteristics as Potential Risk Factors for Anterior Cruciate Ligament Injuries: A Multicentric Cross-Sectional Study. J Clin Med 2024; 13(17):5063. doi: 10.3390/jcm13175063
11. Posch M, Ruedl G, Greier K, Faulhaber M, Tecklenburg K, Schranz A, Burtscher M. Ski-geometric parameters do not differ between ACL injury mechanisms in recreational alpine skiing. Knee Surg Sports Traumatol Arthrosc 2022; 30(6):2141-2148. doi: 10.1007/s00167-021-06852-w
12. Posch M, Ruedl G, Greier K, Faulhaber M, Tecklenburg K, Schranz A, Schliernzauer B, Burtscher M. Impact of Environmental Factors on the ACL Injury Risk in Recreational Alpine Skiing. Int J Sports Med 2023; 44(13):1003-1008. doi: 10.1055/a-2134-3908
13. Posch M, Ruedl G, Schranz A, Tecklenburg K, Burtscher M. Is ski boot sole abrasion a potential ACL injury risk factor for male and female recreational skiers? Scand J Med Sci Sports 2019; 29(5):736-741. doi: 10.1111/sms.13391
14. Posch M, Schranz A, Lener M, Tecklenburg K, Burtscher M, Ruedl G. In recreational alpine skiing, the ACL is predominantly injured in all knee injuries needing hospitalisation. Knee Surg Sports Traumatol Arthrosc 2021; 29 (6):1790-1796. doi: 10.1007/s00167-020-06221-z
15. Promsri A, Longo A, Haid T, Doix AM, Federolf P. Leg Dominance as a Risk Factor for Lower-Limb Injuries in Downhill Skiers-A Pilot Study into Possible Mechanisms. Int J Environ Res Public Health 2019; 16(18):3399. doi: 10.3390/ijerph16183399
16. Ruedl G, Posch M, Tecklenburg K, Schranz A, Faulhaber M, Burtscher M. Skill-Specific Differences in Equipment-Related Risk Factors for ACL Injury in Male and Female Recreational Skiers. Orthop J Sports Med 2023; 11(3):23259671231155841. doi: 10.1177/23259671231155841
17. Ruedl G, Posch M, Tecklenburg K, Schranz A, Faulhaber M, Pocecco E, Burtscher M. A Comparison of ACL Injury Risk, Ski Geometry and Standing Height Parameters between Skiers with Rented and with Owned Skis. Int J Environ Res Public Health 2022; 19(17):11124. doi: 10.3390/ijerph191711124
18. Schmitt KU, Hörterer N, Vogt M, Frey WO, Lorenzetti S. Investigating physical fitness and race performance as determinants for the ACL injury risk in Alpine ski racing.

BMC Sports Sci Med Rehabil 2016; 8:23. doi: 10.1186/s13102-016-0049-6
19. Shimokochi Y, Shultz SJ. Mechanisms of noncontact anterior cruciate ligament injury. J Athl Train 2008; 43(4):396-408. doi: 10.4085/1062-6050-43.4.396
20. Smith C, Grooms DR, Bradley H. Enhancing return to alpine skiing: Integrating perceptual-motor-cognitive considerations in testing and progressions: A clinical commentary. Int J Sports Phys Ther 2024; 19(7):923–34. doi: 10.26603/001c.120285
21. Smith HC, Vacek P, Johnson RJ, Slauterbeck JR, Hashemi J, Shultz S, Beynnon BD. Risk factors for anterior cruciate ligament injury: a review of the literature-part 2: hormonal, genetic, cognitive function, previous injury, and extrinsic risk factors. Sports Health 2012; 4(2):155-61. doi: 10.1177/1941738111428282
22. Spörri J, Kröll J, Amesberger G, Blake OM, Müller E. Perceived key injury risk factors in World Cup alpine ski racing--an explorative qualitative study with expert stakeholders. Br J Sports Med 2012; 46(15):1059-64. doi: 10.1136/bjsports-2012-091048
23. Spörri J, Müller E, Kröll J. "When you're down, stay down": A lesson for all competitive alpine skiers supported by an ACL rupture measured in vivo. J Sport Health Sci 2022; 11(1):14–20. doi: 10.1016/j.jshs.2021.11.004
24. Tarka MC, Davey A, Lonza GC, O'Brien CM, Delaney JP, Endres NK. Alpine Ski Racing Injuries. Sports Health 2019; 11 (3):265-271. doi: 10.1177/1941738119825842
25. Westin M, Harringe ML, Engström B, Alricsson M, Werner S. Prevention of Anterior Cruciate Ligament Injuries in Competitive Adolescent Alpine Skiers. Front Sports Act Living 2020; 2:11. doi: 10.3389/fspor.2020.00011
26. Westin M, Harringe ML, Engström B, Alricsson M, Werner S. Risk Factors for Anterior Cruciate Ligament Injury in Competitive Adolescent Alpine Skiers. Orthop J Sports Med 2018; 6(4):2325967118766830. doi: 10.1177/2325967118766830
27. Westin M, Mirbach LI, Harringe ML. Side-to-side differences in knee laxity and side hop test may predispose an anterior cruciate ligament reinjury in competitive adolescent alpine skiers. Front Sports Act Living 2022; 4:961408. doi: 10.3389/fspor.2022.961408
28. Yu B, Garrett WE. Mechanisms of non-contact ACL injuries. Br J Sports Med 2007; 41 Suppl 1(Suppl 1):i47-51. doi: 10.1136/bjsm.2007.037192